CUKUROVA UNIVERSITY

INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Evaluation of Mechanical Properties of 500 HBW Armor Sheet After Welding With Different Welding Wires and Preheating Temperatures

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Automotive Engineering Department

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ABSTRACT

Armor steels play a crucial role in providing protection against ballistic threats in various applications, including military vehicles, body armors, and structural components. Welding is a widely employed joining technique for armor steels, allowing the fabrication of complex structures with enhanced mechanical properties. However, the welding process can introduce significant changes in the microstructure and mechanical properties of the base material, necessitating a thorough understanding of the effects of welding parameters. This thesis aims to investigate the influence of preheating temperature and welding wire type on the mechanical properties of high-hardness armor (HHA) steels, specifically focusing on the HBW 500 armor plate. The study explores the relationship between preheating temperature, welding wire type, and key mechanical properties such as toughness, hardness, and tensile strength through a comprehensive experimental analysis. As a result, this study has taken significant steps in enhancing our understanding of how preheating temperature and filler wire type affect the mechanical properties of high-strength armor steel. The findings have demonstrated the importance of carefully controlling the preheating temperature and selecting an appropriate filler wire type based on the desired mechanical properties in welded armor structures. The findings from this research will contribute to the optimization of welding procedures for armor steels, enhancing their performance and reliability in demanding applications.

Keywords: Armor, Mechanical Properties, Preheat, Welding, Welding wire.

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

YÜKSEK LİSANS TEZİ

500 HBW Zirh Sacinin Farkli Kaynak Telleri ve Ön Isitma Sicakliklarinda Kaynak Sonrasi Mekanik Özelliklerindeki Değişimi

Fatih AYKILIÇ

Danışman: Dr. Öğr.Üyesi Şafak YILDIZHAN

Otomotiv Mühendisliği Anabilim Dalı

ÖZ

Zırh çelikleri, askeri araçlar, vücut zırhları ve yapısal bileşenler dahil olmak üzere çeşitli uygulamalarda balistik tehditlere karşı koruma sağlamada çok önemli bir rol oynamaktadır. Kaynak, zırh çelikleri için yaygın olarak kullanılan bir birleştirme tekniğidir ve gelişmiş mekanik özelliklere sahip karmaşık yapıların imalatına olanak tanır. Bununla birlikte, kaynak işlemi, kaynak parametrelerinin etkilerinin tam olarak anlaşılmasını gerektirecek şekilde, temel malzemenin mikro yapısında ve mekanik özelliklerinde önemli değişiklikler getirebilir. Bu tez, HBW 500 zırh plakasına odaklanarak, ön ısıtma sıcaklığının ve kaynak teli tipinin yüksek sertlikte zırh çeliklerinin mekanik özellikleri üzerindeki etkisini araştırmayı amaçlamaktadır. Çalışmada, ön ısıtma sıcaklığı, kaynak teli tipi ve tokluk, sertlik ve çekme mukavemeti gibi temel mekanik özellikler arasındaki ilişkiyi kapsamlı bir deneysel analiz yoluyla araştırılmıştır. Sonuç olarak, bu çalışma ön ısıtma sıcaklığı ve kaynak tel tipinin yüksek sertlikteki zırh çeliği üzerindeki mekanik özellikleri nasıl etkilediğine dair anlayışımızı artırmada önemli adımlar atmıştır. Bulgular, ön ısıtma sıcaklığını dikkatlice kontrol etmek ve kaynaklı zırh yapılarındaki istenen mekanik özelliklere bağlı olarak uygun bir kaynak tel tipi seçmek gerektiğini göstermiştir.Bu araştırmadan elde edilen bulgular, zırh çelikleri için kaynak prosedürlerinin optimizasyonuna katkıda bulunacak, zorlu uygulamalarda performanslarını ve güvenilirliklerini artıracaktır.

Anahtar Kelimeler: Zırh Çeliği, Mekanik Özellikler, Ön Isıtma, Kaynak, Kaynak Teli.

GENİŞLETİLMİŞ ÖZET

Zırh malzemeleri, tarih boyunca insanları korumada kritik bir rol oynamıştır. Teknoloji ilerledikçe, zırh malzemelerinde gelişmiş koruyucu özelliklere olan talep artmıştır. Özellikle yüksek sertlikteki zırh (HHA) çelikleri, olağanüstü mukavemet, sertlik, tokluk ve kaynak yapılabilirlik özellikleri nedeniyle popüler bir seçenek haline gelmiştir. Ancak, zırh çelik yapılarının imalatı ve tamirinde kullanılan kaynak işlemi, mekanik özellikler üzerinde, özellikle de mikroyapısal değişikliklerin olduğu ısıdan etkilenen bölge (HAZ) üzerinde önemli bir etkiye sahip olabilir.

Bu çalışmada, yüksek sertlikteki zırh (HHA) çeliğin mekanik özellikleri üzerinde iki ana faktörün, ön ısıtma sıcaklığı ve kaynak tel tipinin etkisini incelenmiştir. Bu odaklanmanın arkasındaki mantık, bu değişkenler ile kaynaklı eklem özelliklerinin sonucu arasındaki karmaşık ilişkiler hakkında detaylı bilgiler ortaya çıkarmak, bu alandaki bilgi birikimine önemli ölçüde katkıda bulunmak ve pratik uygulamalarda optimal sonuçları elde etmek için yönergeler sağlamaktır.

Araştırma, genel olarak tanınan bir HHA çeliği olan 8 mm kalınlığındaki HBW 500 zırh plakasını baz malzeme olarak kullanılmıştır. 300x150x8 mm boyutlarında örnekler hazırlanmıştır. Hazırlanan örnekler MIG kaynak yöntemi ile 20°C, 100°C ve 200°C ön ısıtma sıcaklılarında, ER 110 SG ve ER 307 kaynak telleri ile ayrı ayrı kaynatılmıştır. Kaynak parametreleri, kaynak akımı, voltaj, besleme hızı ve koruyucu gaz bileşimi, tutarlı ve tekrarlanabilir sonuçları sağlamak için optimize edilmiştir.

Hazırlanan numunelere, herhangi bir kusur veya kesintiyi tespit etmek için PT ve UT testleri ve mekanik özelliklerindeki değişimleri incelemek için de; çentik darbe testi, Vickers sertlik testi ve çekme testine tabi tutulmuştur.

Çentik darbe testlerinden elde edilen belirgin bir sonuç, ön ısıtma sıcaklığı arttıkça sünekliğin tutarlı bir şekilde geliştiğiydi. Bu sonuç, ısıl gradyanların kaynak bölgesinde azaltılması sayesinde ısıl etkilenen bölgede (HAZ) daha sünek mikroyapıların oluşması olarak değerlendirilmiştir. Bu çıkarım, zırh çeliğinin kaynak işleminde önemli bir unsur olarak tanımlanmış ve ön ısıtma sıcaklığının dikkatli bir şekilde manipüle edilmesinin, zırh malzemeleri için hayati bir özellik olan üstün darbe direncine yol açabileceğini vurgulanmıştır.

Paralel olarak, Vickers sertlik test sonuçları, ön ısıtma sıcaklığı ile sertlik arasındaki karmaşık etkileşimi ortaya çıkarmış, ki bu da başka bir önemli mekanik özelliktir. ER 110 SG kaynaklı örnekler söz konusu olduğunda, ön ısıtma sıcaklığı 20°C'den 100°C'ye çıkarıldığında ilk başta sertlikte bir artış gözlendi. Bu davranış, mikroyapının incelmesi ve malzeme içindeki ayrışma yoğunluğunun artması sonucu gerçekleştiği değerlendirilmiştir. Bu, malzeme biliminde temel bir kavramdır; burada iyi bilindiği üzere ayrışmalar ve sonraki işlem sertleşmesi, bir malzemenin genel mukavemet ve sertliğine katkıda bulunmaktadır.

Ancak, ön ısıtma sıcaklığı daha da 200°C'ye çıkarıldığında, sertlikte hafif bir azalma kaydedilmiştir. Bu eğilim, mikroyapının irileşmesi ve daha yumuşak fazların olası oluşumu ile ilişkilendirilebilir ve maksimum sertliği elde etmek için optimal bir ön ısıtma sıcaklığı aralığı olabileceğini göstermektedir. Diğer yandan, ER 307 kaynaklı örnekler farklı bir davranış sergilemiş ve ön ısıtma sıcaklığının artmasıyla sertlikte sürekli bir artış göstermiştir. Bu, bu iki değişken arasındaki ilişkinin, kullanılan kaynak tel türüne bağlı olarak önemli ölçüde etkilenebileceğini göstermektedir.

Gerçekten de kaynak tel tipinin seçimi, kaynaklı eklem örneklerinin mekanik özelliklerini önemli ölçüde etkilemektedir. Çekme testi sonuçları bu noktayı açıkça ortaya koymuştur. Hem ER 110 SG hem de ER 307 kaynak telleri, ön ısıtma sıcaklığı arttıkça mukavemetinde bir artışa yol açmıştır. Ancak, süneklik, birçok uygulamada eşit derecede önemli bir mekanik özellik, iki kaynak tel tipi arasında belirgin bir şekilde farklıydı. ER 110 SG örneklerinde ön ısıtma sıcaklığının artmasıyla süneklikte bir azalma yaşanmış, bu durum muhtemelen bu kaynak teli ve HHA çeliği arasındaki spesifik etkileşimler sonucu daha sert, daha az sünek mikroyapıların oluşmasından kaynaklandığı değerlendirilmiştir. Diğer yandan, ER 307 örnekler süneklikte bir artış göstermiş ve bu da daha yüksek ön ısıtma sıcaklığının, bu kaynak tel için güçlülük ve süneklik arasında faydalı bir denge sağladığını düşündürmektedir. Bu kritik bir noktadır, çünkü kaynaklı zırh çeliğinde, her uygulamanın spesifik gereksinimlerine bağlı olarak, mukavemet ve süneklik arasında optimal bir dengeyi elde etmek için kaynak tel tipinin dikkatli bir şekilde seçilmesi gerektiğini vurgular.

Sonuç olarak, bu çalışma ön ısıtma sıcaklığı ve kaynak tel tipinin yüksek sertlikteki zırh çeliği üzerindeki mekanik özellikleri nasıl etkilediğine dair anlayışımızı artırmada önemli adımlar atmıştır. Bulgular, ön ısıtma sıcaklığını dikkatlice kontrol etmek ve kaynaklı zırh yapılarındaki istenen mekanik özelliklere bağlı olarak uygun bir kaynak tel tipi seçmek gerektiğini göstermiştir. Bu bulgular, zırh çeliği kaynak alanındaki gelecekteki araştırma ve geliştirme çabalarını yönlendirmede muhtemelen son derece değerli olacaktır. Ayrıca hem sivil hem de askeri bağlamlarda son derece önemli olan yüksek stres uygulamalarında kaynaklı eklemelerin performansını ve güvenilirliğini artırma potansiyelini vurgulamaktadır.

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SYMBOLS AND ABBREVIATIONS

B	: Bromine
C	: Carbon
Cr	: Crom
H	: Hydrogen
HACC	: Hydrogen Assisted Cold Cracking
HAZ	: Heat Affected Zone
HBW	: Hardness Brinell Tungsten Carbide Ball Indenter
HHA	: High-hardness armor
MAG	: Metal Active Gas
MIG	: Metal Inert Gas
MIG	: Metal Inert Gas
Min.	: Minimum
Mn	: Manganese
Mo	: Molybdenum
N	: Newton
Ni	: Nickel
P	: Phosphorus
PT	: Liquid Penetrant Testing
S	: Sulfur
Si	: Silicon
Temp.	: Temperature
TIG	: Tungsten Inert Gas
UT	: Ultrasonic Testing

1. INTRODUCTION

1.1. Background

From ancient times to the modern era, the evolution of armor materials has mirrored the constant drive to enhance protective capabilities against an ever-evolving spectrum of threats. The historical trajectory of armor technology reflects a fascinating journey, transitioning from rudimentary defenses like bark, animal hides, and felt, to the technologically advanced materials of today, encompassing metals, ceramics, and composites (Schuldies and Nageswaran, 2010; Akella and Naik, 2015). In the contemporary landscape, steel armor has emerged as a cornerstone of defense due to its remarkable attributes – heightened strength, hardness, toughness, and crucially, its weldability, positioning it as the preferred choice among armor materials (Akella and Naik, 2015; Jena and Senthil, 2016).

Armor steels differentiate themselves from conventional steels due to their unique physical and metallurgical attributes, designed specifically to endure the rigorous requirements of shielding against ballistic and explosive threats. Unlike regular steels, armor steels are meticulously formulated to heighten their resilience against projectile penetration and detonation impacts. These improved characteristics result from a blend of factors, including the incorporation of alloying elements, specialized heat treatment procedures, and meticulous control over the microstructure (Kuzmikova, 2013).

Metallurgically, armor steels showcase refined microarchitectures characterized by controlled grain sizes and distributions. This refinement ensures heightened toughness, a critical trait for absorbing and diffusing the energy released upon impact. Moreover, armor steels frequently encompass elevated proportions of alloying components like nickel, chromium, and molybdenum, contributing to enhanced robustness and hardness without compromising weldability. These alloy additions play a pivotal role in augmenting the steel's capability to withstand distortion and fractures even in extreme circumstances. The application of heat treatment stands as another pivotal facet in the manufacture of armor steel, facilitating the formation of specific phases that reinforce the equilibrium between hardness and ductility (Kuzmikova, 2013). The main reasons for the use of high-hardness armor (HHA)in armored vehicle and structures construction are:

Cost Effectiveness: Armor steel is generally more economical in its manufacturing and machining processes. Composite and ceramic armor can be more complex and costly to manufacture. Therefore, using armor steel can sometimes be a more cost-effective option.

Technological Capabilities: Although armor steel is a traditional material, it is strengthened with innovations along with constantly evolving technology. This means that high-quality armor steel can be adapted to more contemporary defense needs.

Ease of Repair: When armor steel is damaged, repairs and maintenance are usually easier. Damages to composite or ceramic armor can be more complex and repairs can take longer.

Impact Resistance and Energy Absorption: Armor steel generally has the ability to absorb a high amount of impact energy. It can provide effective protection against high velocity bullets or explosives. Also, armor steel is generally more durable under sudden impacts.

High Temperature Resistance: Armor steel is more resistant to high temperature conditions. Composite materials may lose their performance or deteriorate under high temperature.

Simple Production and Supply Chain: Armor steel can be produced using traditional metalworking techniques and has an extensive supply chain. This can provide advantages of rapid production and supply.

Although it is widely used due to the advantageous properties of armor steel compared to other armor materials, welding method is generally used as a joining method. Because the welded joint method is low cost, more rigid, long-lasting, less risk of corrosion, lighter and higher strength compared to other joining methods (Bolted joint, bonding, etc.).

Amidst the dynamic arena of tool fabrication, ensuring the mechanical integrity of armor steels takes on paramount significance, particularly when confronted with potential alterations arising from heat exposure during welding processes (Akça and Karaaslan, 2008). A quintessential representative of armor materials is high-hardness armor (HHA) steel, a crucial player in ballistic-resistant applications, notably in the construction of armored vehicles. The pervasive use of welding techniques in the fabrication and repair of HHA steel structures underscores the critical need for a nuanced understanding of the intricate interplay between welding processes and the resultant mechanical properties. Due to the changes in the microstructure of the material due to the heat generated during welding and the different chemical and mechanical properties of the weld wire/electrodes used as filling material, it causes changes in the ballistic and mechanical properties of the welded material. In order to minimize these effects, welding method and welding wire selection and preheating application are of great importance.

It is worth noting that the substantial heat input during welding can catalyze profound microstructural transformations within the steel, significantly impacting its mechanical performance. The judicious selection of welding consumables and the precise application of preheat temperatures emerge as pivotal factors, intricately shaping the metallurgical evolution and consequent mechanical attributes of welded joints (Magudeeswaran et al., 2009).

Against this backdrop, a meticulous exploration of the multifaceted repercussions stemming from distinct welding consumables and preheat temperatures becomes an imperative endeavor. The present study represents a dedicated pursuit aimed at unraveling the intricate relationship between the utilization of ER 110 and ER 307 welding wires and the ensuing mechanical properties of HBW 500 armor steel. The incorporation of diverse preheat temperatures spanning the spectrum from 20°C, through 100°C, to 200°C seeks to meticulously illuminate the profound influence exerted by thermal conditions during the welding process (Jhonson et al., 2019).

1.2. Problem Statement

Welded joint mechanical attributes emerge as a composite outcome of a myriad of parameters intrinsic to the welding process. Among these, two critical parameters stand out: the welding consumable and the preheat temperature. The central focus of this study is a comprehensive exploration of the effects of ER 110 SG and ER 307 welding wires, each distinguished by unique chemical compositions, and consequently, manifesting divergent behaviors, as they interact with the welding process of HBW 500 armor steel. Furthermore, the established understanding that preheating temperature exerts a pivotal role in shaping the post-weld cooling rate, thereby orchestrating intricate microstructural transformations within the heat-affected zone (HAZ), forms a crucial backdrop for this study (Kuzmikova, 2013). Consequently, this study embarks on a meticulous endeavor to elucidate the intricate and multifaceted impact of preheating temperatures set at 20°C, 100°C, and 200°C on the mechanical properties of armor steels.

1.3. Research Objectives

At its core, this research endeavor is fueled by the overarching objective of providing a comprehensive and rigorous evaluation of the intricate interplay between welding parameters and the mechanical properties of HHA steels. This comprehensive assessment is set to unfold through a comprehensive suite of mechanical tests, encompassing the notch impact test, which serves as a litmus test for the material's resistance to brittle fracture, the Vickers hardness test, which offers insights into hardness and potentially strength characteristics, and the tensile test, unravelling the steel's ductility and yield strength.

1.4. Significance of the Study

The ramifications of this study extend far beyond the realm of academic inquiry. By delving deep into the intricate and often subtle influences stemming from the selection of welding consumables and the application of preheating temperatures on the pivotal mechanical properties of armor steels, this study assumes a position of substantial and enduring significance within the body of knowledge. The insights gleaned from this study hold the potential to guide engineers and material scientists in refining and advancing the manufacturing process. The ripple effect of these insights could manifest in a multitude of ways, from heightened efficiency and optimized design of armor steel components to ultimately enhancing the overall performance and efficacy of critical defense systems.

In summary, this study ventures into the intricate nexus of welding processes, welding consumables, preheating temperatures, and their collective impact on the mechanical properties of armor steels. By peeling back, the layers of complexity inherent in this interplay, the study aims to unravel the subtleties and nuances that can drive significant changes in mechanical attributes. In doing so, it aspires to contribute to the ever-growing body of knowledge and, perhaps more critically, to the practical realm of defense and protection, where the performance of armor steels can be pivotal in safeguarding lives and assets.

2. LITERATURE REVIEW

2.1. Welding Techniques and Their Importance

Welding is a common manufacturing method for joining metal parts. This process ensures that different materials or the same materials are combined to form a permanent bond. Welding techniques have various applications in industrial sectors and correct application is important. In this article, the types and importance of welding techniques will be examined in detail.

2.1.1. Welding Techniques

Welding can be accomplished using a variety of methods. Here are some commonly used welding techniques:

2.1.1.1. Arc Welding

Arc welding is a welding method in which materials are joined using an electric arc created using an electrode. This technique falls into several subcategories:

MIG (Metal Inert Gas) Welding: MIG welding is a gas-shielded arc welding technique commonly used in the welding of aluminum or other low-carbon steels. In this method, an inert gas (usually argon or helium) shields the welding area between the electrode and the workpiece. This prevents air and other atmospheric gases from interacting with the molten metal, thus creating a cleaner, stronger weld. The electrode used in MIG welding is typically a wire reel (Duffy, 2003).

MAG (Metal Active Gas) welding, also known as gas metal arc welding (GMAW), is a semi-automatic or automatic process that uses a continuous wire feed as an electrode and an active gas (of carbon dioxide or other gases) as a shielding gas. The electrical power forms an electric arc, which melts the workpiece and the wire, thus creating the weld (Kalpakjian & Schmid, 2014).

TIG Tungsten Inert Gas welding, also known as Gas Tungsten Arc Welding (GTAW), is a method of arc welding that uses a non-consumable tungsten electrode to heat the base metal and create a weld. The welding area and electrode are shielded from oxidation or other atmospheric contamination by an inert gas (such as argon or helium). A filler metal is generally used, though some welds, known as autogenous welds, do not require it. TIG welding is most commonly used to weld thin sections of stainless steel and non-ferrous metals such as aluminum, magnesium, and copper alloys. It provides the operator with greater control compared to most other welding processes, which leads to stronger, higher quality welds. However, TIG is comparatively more complex and difficult to master, and it is significantly slower than most other welding techniques (Weman, 2011).

Electrode Arc Welding: also known as Shielded Metal Arc Welding (SMAW) or stick welding, is a process that uses a consumable electrode covered with a flux to lay the weld. The electrode carries the electric current to the arc and provides filler material. When the welder touches the electrode to the workpiece, the intense heat of the arc melts the surface of the workpiece and the end of the electrode. As the welder moves the electrode along the seam, it creates a puddle of molten metal that solidifies to form the joint. As the electrode melts, the flux covering it also melts, creating a gas that shields the weld from atmospheric contamination and leaves behind a layer of slag that protects the fresh weld from the air (Ghosh, et al, 2017).

2.1.1.2. Gas Welding

Gas welding, also known as oxy-fuel welding, refers to a group of welding processes that use a flame produced by gas, usually oxygen and acetylene, to melt the base material and often a filler material. The molten materials then coalesce and solidify to create the weld joint. This method is typically utilized for welding pipes, tubes, and sheet metal (Weman, 2012).

The welding process begins with the combustion of acetylene with oxygen to produce a flame with a temperature exceeding 3000 degrees Celsius, enough to melt most metals. The gases are stored in separate cylinders and then passed through a hose to a torch where the gases mix. The flame can be adjusted by controlling the gas flow. The process can be autogenous (without filler material), or filler material can be added (Jeffus, 2016).

2.1.1.3. Laser Welding

Laser welding is a process that uses a concentrated beam of light to create high heat in a small area, thus enabling the joining or fusing of different types of materials. The laser beam is focused to the welding area through a lens, and the high-intensity light melts the material and forms a weld pool. Upon cooling, the material solidifies, resulting in a firm joint (Schroeder, 2019).

There are several types of laser welding methods including continuous wave (CW) and pulsed laser welding. The CW method operates with a constant intensity, while pulsed laser welding modulates the laser power in pulses, which is especially useful for thin materials and precise control of the heat input (Leitz,et al., 2020).

2.1.1.4. Resistance Welding

Resistance welding is a method of joining metal sheets by applying a current to a resistance element between the two sheets. The high current, which can range from tens to hundreds of thousands of amperes, is passed through the metal parts for a very short period of time, resulting in a localized melting of the metals to be joined, forming a molten pool. As the current is removed, the molten pool solidifies and forms a solid state bond between the parts. The main advantage of this welding method is that no filler material is required (American Welding Society, 2020).

The main types of resistance welding are spot welding, seam welding, projection welding, and flash welding. These methods vary mainly in the way the current is applied and how the materials are held together during the process (American Welding Society, 2020).

2.1.2. Importance of Welding

Welding techniques play an important role in many industrial sectors. Here are some points where welding techniques are important:

Assembling the Parts: Welding allows large structures and machine parts to be created by putting parts together. Welding techniques are used as an effective method in the process of joining materials.

Ensuring Mechanical Strength: Correct welding techniques and quality welds create a high-strength joint between the joined parts. This increases the durability, load bearing capacity and mechanical performance of structures.

Cost and Efficiency: Welds made by using the right welding techniques save time and material. Efficient welding processes help speed up production processes and reduce costs.

Safety and Quality: Quality welds ensure structures are safe and sound. Well-made welds increase the durability of the structure, reduce potential hazards and prevent unwanted deformations.

2.2. Welding Wire Selection

Welding wires are metal wires used as electrodes during the welding process. These wires provide metal addition to the materials to be melted along the welding arc (Smith, 2019). The right choice of welding wires has a great influence on the quality, strength and durability of the welding process (Johnson, 2017).

While choosing the welding wire, it should be selected according to the mechanical and metallurgical properties of the main material and according to the welding method to be made.

The base material being welded is a primary determinant in welding wire selection. The chemical composition of the wire should be compatible with the base material to ensure a strong and durable weld. For instance, welding carbon steel usually requires carbon steel wire, while stainless steel welding would need a wire made of a similar alloy.

At the beginning of the issues to be considered in the welding of armor steels is the removal of hydrogen from the welding area in order to prevent cold cracking. This makes wire selection important. By using ferritic structured or austenitic stainless steel-containing wires in armor steels, the risk of hydrogen-induced cracking is eliminated due to their high hydrogen solubility in the austenic phase (Magudeeswaran et al. 2018).

2.2.1. Types of Welding Wires

Welding wires come in different materials and coatings (Brown, 2020). Different types of welding wires are available, especially for commonly used metals such as steel, aluminum, copper and nickel (Johnson, 2017). The material selection of welding wires depends on the demands of welding applications and material properties.

2.2.1.1. Steel Welding Wires

Steel welding wires are manufactured from various steel alloys (Smith, 2019). These wires are widely used in structural welding applications, industries such as automotive, construction and shipbuilding (Brown, 2020). Steel welding wires come in different carbon content, durability and welding properties.

2.2.1.2. Aluminum Welding Wires

Aluminum welding wires are used for welding aluminum and aluminum alloys (Johnson, 2017). Aluminum has a wide range of uses in industries such as aerospace, automotive and shipbuilding (Smith, 2019). Aluminum welding wires are specially designed considering the low melting point and high conductivity properties of aluminum.

2.2.1.3. Copper and Copper Alloy Welding Wires

Copper and copper alloy welding wires are used in applications that require electrical conductivity (Brown, 2020). It is preferred in areas such as electrical wiring, electronic circuits, plumbing and copper pipe welding (Johnson, 2017). Copper welding wires are specially designed to provide the high conductivity and thermal properties of copper.

2.2.1.4. Nickel and Nickel Alloy Welding Wires

Nickel and nickel alloy welding wires are used in applications that require high temperature and corrosion resistance (Smith, 2019). They are widely used in industries such as the chemical industry, power generation, marine and petrochemicals (Brown, 2020). Nickel welding wires are designed taking into account the special properties of nickel and nickel alloys.

2.2.2. Selection Criteria for Welding Wires

Correct selection of welding wires is vital for a successful welding process (Johnson, 2017). Here are some criteria to consider in the selection of welding wires:

2.2.2.1. Material Compatibility

The material selection of the welding wire should be suitable for the type of material to be joined (Smith, 2019). Material compatibility is critical to the durability and strength of the weld joint (Brown, 2020).

2.2.2.2. Welding Practice and Conditions

Welding application and conditions should be considered in selecting the right welding wire (Johnson, 2017). Factors such as welding method, welding position, material thickness, welding speed and welding environment may bring different requirements depending on the characteristics and coating of the welding wire (Smith, 2019).

2.2.2.3. Welding Performance and Characteristics

The performance and properties of welding wires are important factors affecting welding results (Brown, 2020). Properties such as strength, crack resistance, corrosion resistance, weld deformation, heat treatment requirements should be considered in the selection of welding wire (Johnson, 2017).

2.2.2.4. Cost and Efficiency

The cost and efficiency of the welding wire are factors to be considered in the selection process (Smith, 2019). At the same time, factors such as welding speed, efficiency and quality of welding results should be considered (Brown, 2020).

2.2.3. Characteristics and Applications of ER 110 SG and ER 307 Welding Wires

Welding consumables, specifically welding wires, play a crucial role in determining the quality of the weld joint. These welding wires differ in their chemical composition, which influences their behavior during the welding process and the microstructure of the fusion zone.

In this study, ER 110 SG and ER 307 welding wires, commonly used in industry, are examined.

ER 307 is a type of ferritic welding wire which is a type commonly used for welding armor steels. This wire has the property of expansion such as high strength, impact strength and growth resistance. ER 110 SG welding wire can improve the post-weld mechanical properties of steel samples and increase strength. The chemical structure of ER 110 SG welding wire shown in Table-2.1 and its mechanical properties shown in Table-2.2

Table 2.1. ER 110 SG Chemical Composition of Welding Wire% (Typical) (“Anonymous 4”, n.d.)

C	Si	Mn	Mo	Ni	Cr	Cu
0.09	0.75	1.70	0.50	2.0	0.30	020

Table 2.2. ER 110 SG Welding Wire Mechanical Properties (“Anonymous 4”, n.d.)

Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)	Impact Strength (ISO-V/-30°C)	Elongation ((Lo=5do) (%)
min. 690	min. 760	min. 47 J	19

ER 307 is a type of authenticate welding wire which is another type used for welding armor steels. This wire performs well especially in high temperature working conditions. ER 307 welding wire can increase crack resistance and reduce thermal deformation in steel samples. The chemical structure of ER 307 welding wire shown in Table-2.3 and its mechanical properties are in Table-2.4.

Table 2.3 ER 307 Chemical Composition of Welding Wire% (Typical) ("Anonymous 3", n.d.)

C	Si	Mn	Cr	Ni
0,08	0,9	7,0	19,2	9,0

Table 2.4 ER 307 Welding Wire Mechanical Properties ("Anonymous 3", n.d.)

Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)	Impact Strength (ISO-V/+20°C)	Elongation ((Lo=5do) (%))
Min. 370	580-750	min. 63 J	Min. 30

2.3. Preheating in Welding

It's a standard procedure to preheat steel before welding and manage the temperature between passes, in order to mitigate the likelihood of hydrogen-assisted cold cracking (HACC) in welded structures. This process not only removes moisture from the surface of the plate but also reduces the cooling rate. This slower cooling results in a less rigid microstructure and allows for sufficient time for hydrogen to disperse from the weldment. Moreover, it reduces residual stresses. Hence, this method successfully addresses all three elements that contribute to HACC. (Prifti et al, 1997).

The selection of the preheating temperature is a critical factor, with different optimal temperatures reported for different types of steel. Recent research indicates that the preheating temperature can significantly affect the mechanical properties of the welded joint. However, there is a trade-off, as excessively high preheating temperatures can lead to other issues, such as the formation of coarse grains that can reduce the steel's strength and toughness (Gürol et al, 2022).

Since heat loss may occur from the surface during the welding process of thick section armor steels, it may be necessary to preheat the armor steels to ensure weldability. It is recommended that the preheat temperatures be between 75-300°C depending on the part thickness. (Gürol et al, 2022).

2.4. Armor Steels

Armor steels, or high-hardness armor (HHA) steels, are a unique class of steel that exhibit a significant resistance to impact and penetration. Owing to their extraordinary hardness, strength, and toughness, these steels find widespread applications in military and defense sectors, primarily in the manufacture of armored vehicles and structures (Serrano and al, 2022). Over the years, considerable advancements in metallurgy and materials science have led to improvements in the composition and processing of armor steels, enhancing their mechanical and ballistic properties.

2.4.1. Overview of Armor Steels

Armor Steels against single and multiple strikes of projectiles, explosive and fragmenting warheads and mines; They are high quality homogeneous micro-structured, low carbon alloy steels that are frequently used in military vehicles in order to resist the effects of cracking, rupture and fracture.

Features expected from armor steels.

- High resistance to ballistic impacts
- Ease of production operations
- Long lifetime

There are NATO quality standards used as a reference to the strength properties of armor steels. These are MIL-A12560 and MIL-A46100. The hardness value for MIL-A12560 Class I varies according to different plate thicknesses and is defined as 300-430 HBW. For the Class II version of the same standard, although the hardness value drops to 280 HBW, the impact strength rises to 40 J. The same is true for the MIL A46100 quality standard. For this quality standard, the hardness value reaches 500 HBW and the tensile strength reaches 1800N/mm2. Table-2.5 lists the mechanical properties obtained from some steel producers.

Table 2.5 Mechanical Properties Some Armor Steels ("Anonymous 1", n.d.; "Anonymous 2", 2012)

Armor Steel	**Thickness (mm)**	**Yield Strength (N/mm^2)**	**Tensile Strength (N/mm^2)**	**Elongation (%)**	**Impact Strength (ISO-V/-40°C) (Joule)**	**Hardness Range (HBW)**
Miilux 380	6-25	800	1000	12	20 J	320-370
Miilux 400	5-40	1000	1250	10	30 J	360-420
Miilux 450	5-40	1200	1450	8	30 J	420-480
Miilux 500	2,5-40	1250	1600	8	20 J	480-560
Armox 370T	3-100	800	1100	13	60 J	280-330
Armox 440T	4-80	1000	1250-1550	10	45 J	420-480
Armox 500T	3-80	1250	1450-1750	8	32 J	480-540

2.4.2. Physical Metallurgy of Armor Steels

It is expected that armor steels will show resistance against all kinds of destructive (crack, piercing, disintegrating, etc.) effects that may come from the outside. This resistance is only possible if the properties of high strength, hardness and toughness are homogeneous throughout the material (Balakrishnan et al., 2012).

As shown in Table 2.6, the most commonly used armor steels, such as Miilux 500, Armox 500T, and Ramor 500, are found to contain various alloying elements in addition to their base alloying elements. These additional alloying elements include boron (B), titanium (Ti), vanadium (V), niobium (Nb), and others.

Table 2.6. Chemical composition of commonly used commercial armor steels ("Anonymous 1", n.d.; "Anonymous 2", 2012)

Content % Max.	Miilux 500	Ramor 500	Armox 500T
C	0,3	0,35	0,32
Si	0,7	0,7	0,4
Mn	1,7	1,5	1,2
P	0,03	0,0015	0,015
S	0,015	0,01	0,01
Cr	1,5	1	1
Ni	0,8	2	1,8
Mo	0,5	0,7	0,7
B	0,004	0,005	0,005

2.4.3. Welding of Armor Steels

Welding is a common manufacturing process in the fabrication and repair of armored steel structures. However, the high temperatures involved in the welding process can cause substantial changes in the microstructure of the armor steels, particularly in the heat-affected zone (HAZ) and the weld metal. These microstructural changes can affect the hardness, tensile strength, ductility, and impact toughness of the material post-welding. This transformation is critical because it could lead to a potential reduction in the ballistic performance of the steel, thereby compromising the safety and integrity of the armor structure (Kuzmikova, 2013).

The HAZ is a region of particular interest because it undergoes significant microstructural transformations, resulting from the heating and subsequent cooling associated with the welding process. Various phases may form in the HAZ, including martensite, bainite, or more complex microstructures, depending on the cooling rate and the specific composition of the steel. These phase transformations can have a significant impact on the mechanical properties of the steel in the HAZ, often leading to embrittlement or a reduction in hardness (Prifti et al, 1997).

Quality standards in the welding of MIL STD 1185 and SD-X12140D armor steels are defined. When these standards are examined, in general, it is the protection of mechanical properties and the provision of welding strength in order to ensure a long service life expected from armor steels (MIL

STD 1185, 1979; SD-X12140D, 1987). In order to ensure weld strength, there should be no weld gaps, cracks, slag residues, pores or burning grooves as a result of the welding process (Robledo et al. 2010; Kara, 2012).

2.5. Previous Studies on Welding of Armor Steels

A review of the existing literature indicates that numerous studies have been conducted on the welding of armor steels. However, most have tended to focus on individual aspects such as the effect of heat input, welding speed, filler material, and shielding gas composition. Comprehensive studies investigating the combined effects of different welding wires and preheating temperatures on the mechanical properties of welded armor steels are less common. This represents a knowledge gap that this study aims to fill.

2.6. Mechanical Testing of Armor Steels

Mechanical testing plays a crucial role in evaluating the performance of armor steels post-welding. The tests to be used in this study include the notch impact test, the Vickers hardness test, and the tensile test. The notch impact test measures the energy absorbed during fracture, providing an assessment of the material's toughness. The Vickers hardness test is a method of measuring the hardness of the material, which is a critical factor in the steel's resistance to penetration. The tensile test, on the other hand, provides information on the ductility and yield strength of the steel, which are crucial properties under service conditions.

3. MATERIALS AND METHODS

3.1. Materials

The base material for this study was 8 mm thickness HBW 500 armor plate, which is a high hardness armor (HHA) steel widely used in ballistic protection applications. HBW 500 steel is known for its exceptional hardness, strength, and toughness, making it suitable for resisting high-velocity impacts. The HBW 500 armor plate used in this study was sourced from a steel supplier and met all requisite industry standards. The mechanical properties HBW 500 armor steel shown in Table-3.1 and its chemical structure are in Table-3.2.

Table 3.1. HBW 500 Hardness Armor Plate Mechanical Properties “Anonymous 2”, 2012)

Yield Strength (N/mm2)	**Tensile Strength (N/mm2)**	**Impact Strength (ISO-V/-40°C)**	**Elongation A5 (%)**	**Hardness Range HBW**
1250	1600	20 J	8	480-540

Table 3.2. HBW 500 Hardness Armor Plate Chemical Composition Maximum % “Anonymous 2”, 2012)

C	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Mo**	**B**
0,3	0,7	1,7	0,03	0,015	1,5	0,8	0,5	0,004

The test samples were taken from 500 HBW sheet metal with the dimensions of 300x150x8 mm, and the welding groove was created with the milling method according to TS EN ISO 9692-1 standard as shown in Figure-3.1.

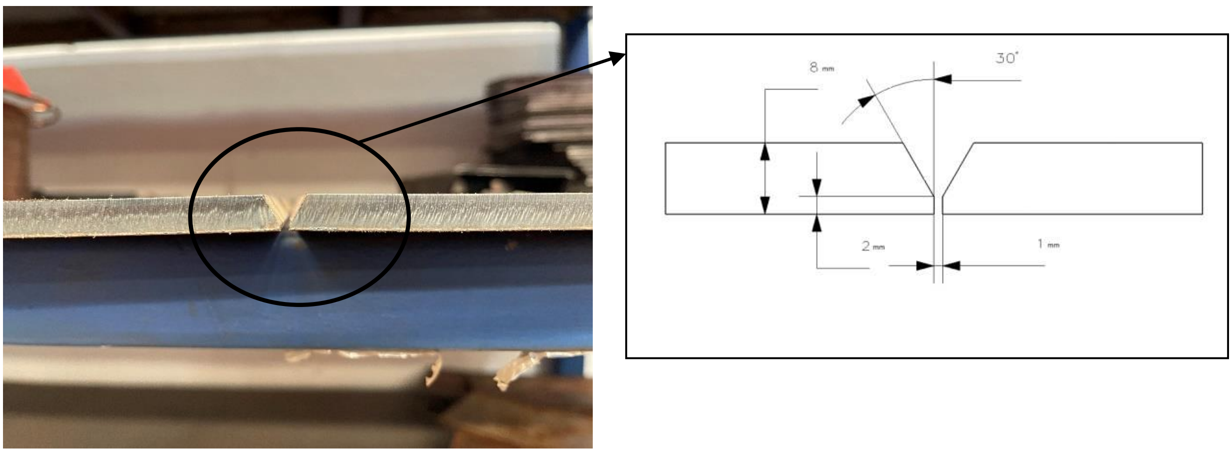

Figure 3.1. Welding Plate Sample

3.2. Preheating and Welding

Three different preheating temperatures were chosen to investigate the effect of preheating temperature on the mechanical properties of welded joints: 20°C, 100°C and 200°C. Preheating was done with propane torch (Figure-3.2). Sample temperature was measured with temperature indicating crayon (Figure-3.3).

Figure 3.2. Preheating With Propane Torch

Figure 3.3. Temperature Indicating Crayon

3.3. Welding Procedures

Welding procedures were performed following standard industry practices. Before welding, the HBW 500 armor plate was carefully prepared by cleaning the surfaces to ensure optimum weld quality. The welding process used for this work was gas metal arc welding (GMAW), also known as MIG welding, model TPS 500i from Fronius (Figure 3.4). Technical properties are listed in Table 3.3.

Figure 3.4. Welding Machine

Table 3.3 Fronius TPS 500i Technical Data (“Anonymous 7”, n.d.)

Property	Value
Mains voltage	3 x 400V
Mains frequency	50-60Hz
Welding current min.	3:00 ÖÖ
Welding current max.	500 A
Welding current / Duty cycle [10min/40°C]	500A / 40%
Welding current / Duty cycle [10min/40°C]	430A / 60%
Welding current / Duty cycle [10min/40°C]	360A / 100%
Open-circuit voltage	71 V
Degree of protection	IP23
Length	706 mm
Width	300 mm
Height	510 mm
Weight	38 kg
Interference emission class	A

Two types of welding wire were used in this study: ER 110 SG and ER 307. ER 110 SG is a low alloy steel filler metal known for its excellent strength and toughness properties, while ER 307 is an austenitic stainless steel filler metal with superior oxidation resistance. Both welding wires were selected according to their suitability for welding high-strength steels and their different chemical compositions.

Welding parameters such as welding current, voltage, feed rate and shielding gas composition were optimized based on preliminary trials and recommendations from industry standards (Table-3.4). These parameters were kept constant throughout the welding process to ensure the consistency and reproducibility of the results.

Table 3.4. Welding parameters

Property	**Value**
Shielding Gas Composition	Ar+15-20%CO2
Voltage	23
Current	180

Multiple welds were made using both ER 110 SG and ER 307 welding wires for each preheat temperature (Table-3.5). Welds were made on separate samples to avoid any contamination or interference between different welding wires. Welding was carried out carefully to ensure proper fusion and penetration, and the resulting welded joints were visually inspected for any defects or discontinuities.

Table 3.5. Welding preheats temperatures and used welding wire

Preheating Temperature	**ER 110**	**ER 307**
20°C	x	x
100°C	x	x
200°C	x	x

3.4. Mechanical Testing

After welding, the specimens were subjected to a series of mechanical tests to evaluate their mechanical properties. The tests performed included:

3.4.1. Liquid Penetrant Testing (PT)

Welded samples were visually inspected according to EN ISO 13018:2016, EN ISO 5817:2010, EN ISO 17837:2017 and EN ISO 6520-1:2018 standards. Liquid penetrant tests were carried out in accordance with EN ISO 3452-1:2021, EN ISO 3452-2:2021, EN ISO 3059:2013 and EN ISO 23277:2016 standards. Penetrant (the liquid with suitable properties) is deposited on the clean and dry surface of the part to be examined. Penetrant needs some "penetration" time to penetrate the surface opened imperfections. After this dwell time the excess penetrant shall be removed from surface and the developer is deposited on the surface. The developer is strong absorber and withdraws the penetrant from discontinuities to the surface. After developing time it is possible to inspect presence of two-dimensional indications. Advantage is, that imperfections that are so small to be visible by human eyes, create larger indications. These indications create high contrast (color or brightness) on the background. Imperfection is detectable approximately from the width of microns.

3.4.2. Ultrasonic Testing (UT)

Ultrasonic testing (UT) is a non-destructive testing (NDT) method widely used in industries such as aerospace, automotive, power generation, and petrochemical to examine the internal structure of a material or component. UT works by sending high-frequency sound waves into the material and then analyzing the reflected waves. By evaluating the reflected waves, technicians can determine the size and location of any flaws or discontinuities within the material. The tests were carried out with the USM 36 Krautkramer test device according to TS EN 17640 Level B and TS EN ISO 11666 Level 2. Test device is in Figure 3.5. Technical properties are listed in Table 3.6.

Figure 3.5. USM 36 Krautkramer Welding Ut Test Machine

Table 3.6. USM 36 Krautkramer Welding Ut Test Machine Technical Specifications ("Anonymous 8", n.d.)

Property	Value
Pulser mode	Spike pulser, optionally: Square-wave pulser
Pulser voltage (SQ mode)	120 … 300 V, in steps of 10 V with a tolerance of 10%
Pulser falling/rising time	max. 10 ns
Pulser width (SQ mode)	30 … 500 ns, in steps of 10 ns
Pulser amplitude (Spike mode)	low: 120 V, high: 300 V
Pulser energy (Spike mode)	low: 30 nS, high: 100 nS
Damping	50 ohms, 1000 ohms
Digital gain	Dynamic range 110 dB, adjustable in steps of 0.2 dB
Analog bandwidth	0.5 … 20 MHz
Equivalent input noise	<80 nV/√Hz
Filters	Broadband: 1-5 MHz / 2, 2.25 MHz / 4, 5 MHz / 10 MHz / 13, 15 MHz
Rectification	Positive half-wave, negative half-wave, full wave, RF signal

3.4.3. Notch Impact Test

Notch impact test is a test method used to evaluate the toughness and fracture behavior of a material. In this test, notches with predetermined geometries are applied to the material, and the fracture behavior beneath the notch is examined.

The notch impact test is commonly used to assess the mechanical properties of metal materials. The test is conducted by applying a specific amount of energy to a notched specimen of the material. This energy can be provided using a specialized hammer or impact device.

When a impact is applied to the notched sample during the test, the material either fractures or cracks form along the notch. The fracture behavior occurring beneath the notch provides important information about the material's toughness and resistance to fracture.

This test measures the energy absorbed by the specimen during fracture and provides an indication of its toughness and resistance to brittle fracture. Three test samples have been taken from each welded plate. These samples are numbered from VWT-1 to VWT-18. The test result is calculated by taking the average of these three samples. The notch impact test was performed with Hardway Computer-Controlled Notch Impact Test Machine in accordance with TS EN ISO 9016 standard. Test device is in Figure 3.6 Technical properties are listed in Table 3.7.

Figure 3.6. Hardway Computer-Controlled Notch Impact Test Machine

Table 3.7. Hardway Computer-Controlled Notch Impact Test Machine Technical Specifications (“Anonymous 10”, n.d.)

Property	Value
Impact Energy	150 J / 300 J
Control Methods	Single Chip Control
Display Way	Dial Display and Digital Display
The Distance Between The Pendulum Shaft And Impact Point	750 mm
Minimum Reading Value	1 J
Impact Speed	5.2 m/s
Pre-rising Angle Of The Pendulum	150°
Specimen Bearer Span	40+0.2 mm
Round Angle Of The Jaw	R 1.0~1.5 mm
Round Angle Of Impact Edge	R 2.0~2.5 mm (Optional: R8±0.05 mm)
Angle Accuracy	0.1°
Pendulum Torque	M=160.7695N.m 80.3848N.m
Standard Specimen Dimension	10 mm * 10(7.5 or 5) mm * 55 mm
Impact Pendulum Configuration	150 J, 1 PC; 300 J, 1 PC
Power Supply	3phs, 380V, 50Hz
Dimensions	2124 * 600* 1340 mm
Net Weight	480 KG

3.4.4. Vickers Hardness Test

Hardness can be defined as the resistance of materials to scratching. The hardness values naturally depend on the experimental conditions. Hardness tests are one of the most important mechanical tests that provide quick and non-destructive control of materials and manufactured parts.

Hardness measurement methods commonly used in technology are methods based on the measurement of permanent traces obtained on the sample.

Vickers hardness test experimental approach involves using a diamond square pyramid with an apex angle of 136° as a printing tool. The final results are determined by substituting the average diagonal length formulas, which are obtained by measuring the diagonals of the rectangular impression made by the pyramid's tip pressing into the material under a load of F. Vickers hardness is not influenced by the applied load. To minimize measurement errors and obtain an average value in structures with varying properties, it is recommended to increase the load and the size of the impression. However, the hardness measurements based on diagonal length should not exceed two-thirds of the thickness of the part or layer being tested. The load can range from 1 to 120 kgf, with 30 kgf being the typical standard load. Despite the small indentation depths created by large pyramids, the Vickers method produces wide diagonal measurements. The duration of the load on the sample is approximately 20 seconds. Once this period elapses, the pressure tip is removed from the sample, and the test concludes. (“Anonymous 6”, 2022)

Vickers hardness test measures the hardness of welded joints and gives information about their resistance to indentation. The test was carried out using a Vickers hardness tester HARDWAY-DHV10 MMP conforming to TS EN ISO 9015-1 standard. Test machine is in Figure 3.7. Technical properties are listed in Table 3.8.

Figure 3.7 Vickers Hardness Test Machine HARDWAY-DHV10 MMP

Table 3.8. Vickers Hardness Test Machine HARDWAY-DHV10 MMP Technical Specifications (“Anonymous 11”, n.d.)

Property	**Value**
Objective lens and Indenter type	Manuel Turret
Test Load	300g (1.96N) 500g (4.9N) 1kg (9.8N) 3kg (29.4N) 5kg (49N) 10kg (98N)
Test Scale	HV0.3 - HV0.5 - HV1 - HV3 - HV5 - HV10
Min.Unit Measurement	0.5µm
Hardness Value Range	8HV-3000HV
Hardness reading display	Dijital LCD
Microscope Total Magnification	100X (For Observation), 200X (For Measurement), (Optionally Magnified 400X)
Loading Method	Automatic (loading, standby and test force lifting)
Cooldown	1-99s
Max.Height	160 mm
Body Distance from Indentor Center	130 mm
Dimensions	530×220×580mm
Weight	55 kg
Light Source	LED Cold light source
Power Supply	220V + 5%, 50/60 Hz
Data Output	Internal Printer
Standards conforming to	TS EN ISO 6507 / ASTM E 384 / GB/T4340.2

3.4.5. Tensile Test

The tensile test, also known as a tension test, is a common mechanical test used to determine the mechanical properties of a material, particularly its response to applied forces or loads. It involves subjecting a test specimen to an axial pulling force in order to measure how the material behaves under tension.

During a tensile test, a standardized test specimen, usually in the form of a cylindrical or rectangular shape, is gripped at each end by specialized grips. The grips then exert opposing forces, gradually increasing the applied load in a controlled manner. This causes the specimen to elongate until it eventually breaks.

Throughout the test, various parameters are measured, including the applied load and the corresponding elongation or deformation of the specimen. These measurements are used to calculate important mechanical properties, such as tensile strength, yield strength, modulus of elasticity, and ductility.

This test measures the tensile strength, yield strength, and elongation of the welded joints, providing insights into their mechanical behavior under tensile loading. The tensile test was carried out according to the TS EN ISO 4136 standard, with a WAW 600 D testing machine. Test machine is in Figure 3.8. Technical properties are listed in Table 3.9.

Figure 3.8 WAW 600 D Tensile Test Machine

Table 3.9 WAW 600 D Technical Specifications ("Anonymous 9", n.d.)

Property	Value
Structure	4 columns and 2 screws
Control way	Constant stress uniform deformation constant displacement three closed loop control and program control dealing
Max.load (kN)	600kN
Load accuracy	≤±1%
Load range	2%-100%FS
Load resolution	1/300000
Deformation Measurement Range	2%～100%FS
Deformation accuracy	≤±1%
Displacement resolution (mm)	0.01
Displacement error	≤±0.5%
Max.piston stroke(mm)	250

Max piston moving speed	0-90mm/min stepless speed adjusting
Crosshead lifting speed	200mm/min
Max. tension test space	650mm (can customize)
Max.Compression Test Space	500mm (can customize)
Column clearance(mm)	475
Clamping method	Hydraulic clamp
Round specimen clamping range (mm)	Φ13-Φ26,Φ26-Φ40, (Φ6-Φ13 , Φ40-Φ50 Optional)
Flat specimen clamping range (mm)	0-15 (15-30 Optional)
Flat specimen clamping width(mm)	80
Compression plate size (mm)	φ160
Bending roller distance(mm)	450
Width of bending rollers (mm)	120
Power supply	3-phase, AC380V, 50Hz (can be customized)

3.4.6. Data Analysis

The data obtained from the mechanical tests results were interpreted to draw meaningful conclusions and insights into the effect of preheating temperature and welding wire type on the mechanical properties of the HBW 500 armor plate.

4. RESULTS AND DISCUSSIONS

4.1. Results

A series of tests were carried out to observe the changes in the mechanical properties of 500 HBW armor sheet after welding with ER 110 SG and ER 307 welding wires at 20°C, 100°C and 200°C preheating values. A welded sample shown in Figure 4.1. A notch impact test was used to assess the material's resistance to fracture, a Vickers hardness test to determine hardness and potentially strength, and a tensile test to understand the ductility and yield strength of the steel. In addition, PT and UT tests were performed to evaluate the suitability of the weld.

The welded samples are coded and the coding type is given in Table 4.1.

Figure 4.1. A Welded Sample

Table 4.1. Welded Samples Codes

Welding Wire	Preheat Temperature	Sample Number
ER 110 SG	20°C	110-20
ER 110 SG	100°C	110-100
ER 110 SG	200°C	110-200
ER 307	20°C	307-20
ER 308	100°C	307-100
ER 309	200°C	307-200

4.1.1. Liquid Penetrant Testing (PT)

PT was performed to inspect the process of the samples welded. Tested samples are in Figure-4.2. Welded samples were visually inspected according to EN ISO 13018:2016, EN ISO 5817:2010, EN ISO 17837:2017 and EN ISO 6520-1:2018 standards. Liquid penetrant tests were carried out in accordance with EN ISO 3452-1:2021, EN ISO 3452-2:2021, EN ISO 3059:2013 and EN ISO 23277:2016 standards and no welding imperfection were detected.

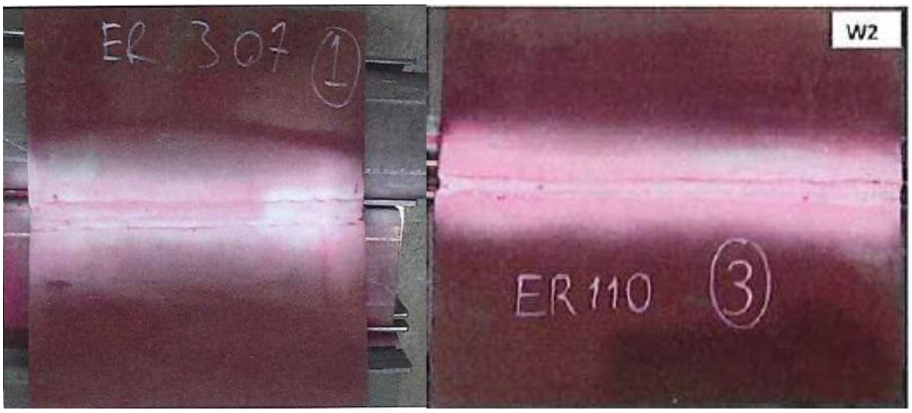

Figure 4.2. PT Tested Samples

4.1.2. Ultrasonic Testing (UT)

UT was performed to inspect the examination of the process of the samples welded. No welding imperfection were detected according to TS EN 17640 Level B and TS EN ISO 11666 Level 2 standard.

4.1.3. Notch Impact Test Results

A thorough analysis was conducted on the energy absorbed by the welded samples. Test conditions are in Table-4.2 and Test results are shown in Table-4.3 and Figure 4.4. Tests and sample preparation were carried out according to the TS EN ISO 9016 standard. Tested samples shown in Figure 4.3.

For both ER 110 SG and ER 307 welded samples, an deccrease in preheat temperature corresponded to a significant improvement in the material's toughness. This negative correlation between preheat temperature and toughness validates earlier findings in the existing literature.

Table 4.2. Notch Impact Test Conditions

Property	Value
Test Machine	Hardway Computer-Controlled Notch Impact Test Machine
Temperature	20ºC
Humidity (%)	%51
Test Standard	TS EN ISO 9016
Test Method	CHARPY
Notch Type	V-NOTCH
Sample dimensions	7,5X10X55

Figure 4.3. Notch Impact Test Samples After Tests

Table 4.3. Notch Impact Test measurements

Item No	Sample No	Denomination	Imp. Toug.	Impact Absorbed Energy (J)	Average Impact Energy (J)
		VWT-1	62	37,2	
1	110-20	VWT-2	74	44,4	41,6
		VWT-3	72	43,2	
		VWT-4	55	33	
2	110-100	VWT-5	52	31,2	35,2
		VWT-6	69	41,4	
		VWT-7	39	23,4	
3	110-200	VWT-8	47	28,2	27,4
		VWT-9	51	30,6	
		VWT-10	77	46,2	
4	307-20	VWT-11	77	46,2	48,6
		VWT-12	89	53,4	
		VWT-13	68	40,8	
5	307-100	VWT-14	83	49,8	45,4
		VWT-15	76	45,6	
		VWT-16	85	51	
6	307-200	VWT-17	64	38,4	43,8
		VWT-18	70	42	

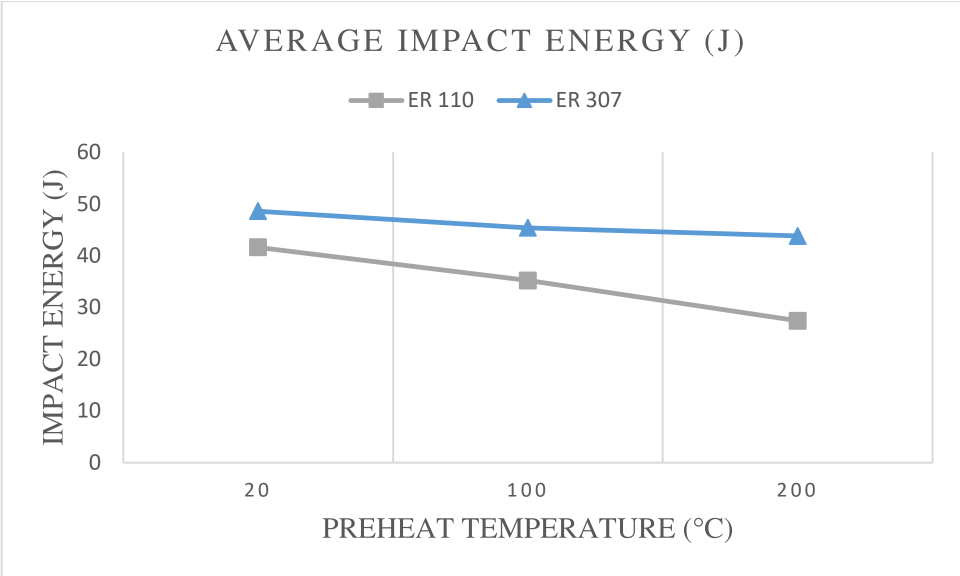

Figure 4.4. Notch Impact Test measurements

4.1.4. Vickers Hardness Test Results

The Vickers hardness test results provided insights into the resistance of the welded armor steel to deformation. Test conditions are in Table-4.4, testing locations are in Figure 4.4 and test results are shown in Table-4.5 and Figure 4.6. The ER 110 SG welded samples demonstrated an intriguing hardness trend. As the preheat temperature escalated from 20°C to 100°C, a noticeable increase in hardness was observed, pointing to the formation of a denser and more rigid microstructure. However, when the preheat temperature was further augmented to 200°C, a slight decrease in hardness ensued. This may be attributed to possible grain growth at higher temperatures, leading to a reduction in hardness. Conversely, the ER 307 welded samples exhibited a consistent and linear increase in hardness with increasing preheat temperature, indicating a direct relationship between preheating and hardness in ER 307 welded joints.

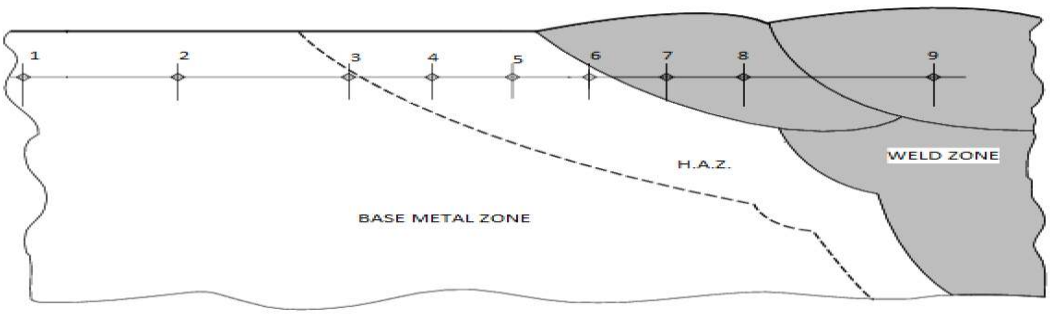

Figure 4.5. Vickers Hardness Testing Locations

Table 4.4 Vickers Hardness Test Conditions

Property	**Value**
Test Machine	HARDWAY-DHV10 MMP
Temperature	23 °C
Humidity (%)	%45
Test Standard	TS EN ISO 9015-1

Table 4.5 Vickers hardness measurements

	Measured Hardness (HBW								
Sample No	**Base Metal Zone**			**H.A.Z Zone**			**Weld Zone**		
	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8	Point 9
110-20	406	396	402	438	424	431	288	286	285
110-100	389	387	392	359	355	361	297	290	292
110-200	396	412	408	415	421	418	281	283	288
307-20	455	462	465	535	517	521	234	238	236
307-100	471	462	465	468	470	470	269	272	275
307-200	471	472	468	463	469	471	388	326	321

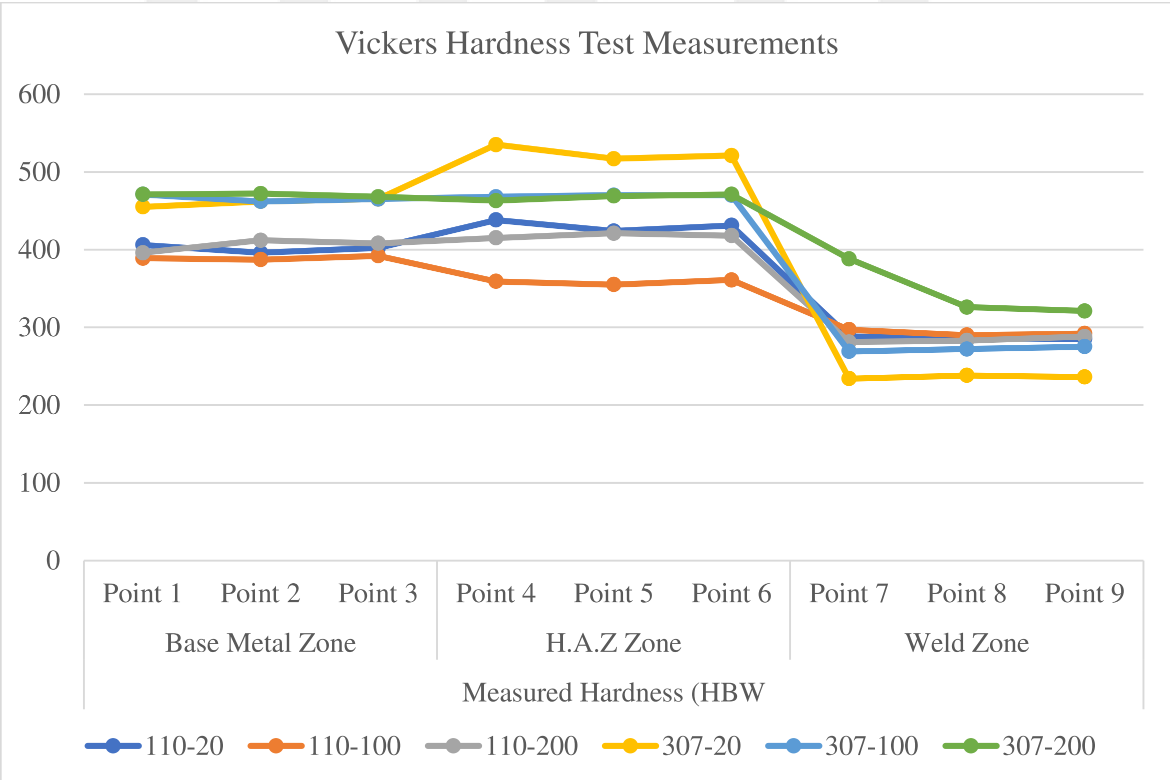

Figure 4.6. Vickers hardness measurements

4.1.5. Tensile Test Results

The tensile test results offered comprehensive data on the yield strength and ductility of the welded samples. Test conditions are in Table 4.6. Tested samples shown in Figure 4.5. As detailed test results in Table 4.7 and Figure 4.14. In addition, the results for each test are separately shown in Figure 4.8, Figure 4.9, Figure 4.10, Figure 4.11, Figure 4.12, Figure 4.13. In the tests performed on ER 307 welded samples, it was observed that they were broken in the elastic deformation region before reaching the plastic deformation region... Therefore, the yield strength could not be measured. However, the ductility results provided a contrasting narrative. While the ER 307 samples demonstrated an increase in ductility with increasing preheat temperature, indicating enhanced malleability and toughness, the ER 110 SG samples manifested a decrease in ductility under the same conditions. This inverse relationship for ER 110 SG samples indicates a trade-off between increased strength and reduced ductility with increasing preheat temperature.

Table 4.6. Tensile Test Conditions

Property	Value
Test Machine	WAW 600D
Temperature	23°C
Humidity (%)	52%
Test Standard	TS EN ISO 4136
Test Speed	20 mm/Min
Measuring Length	80 mm
Sample Thickness	8,3 mm
Sample witdth	25 mm

Figure 4.7. Tensile Test Samples

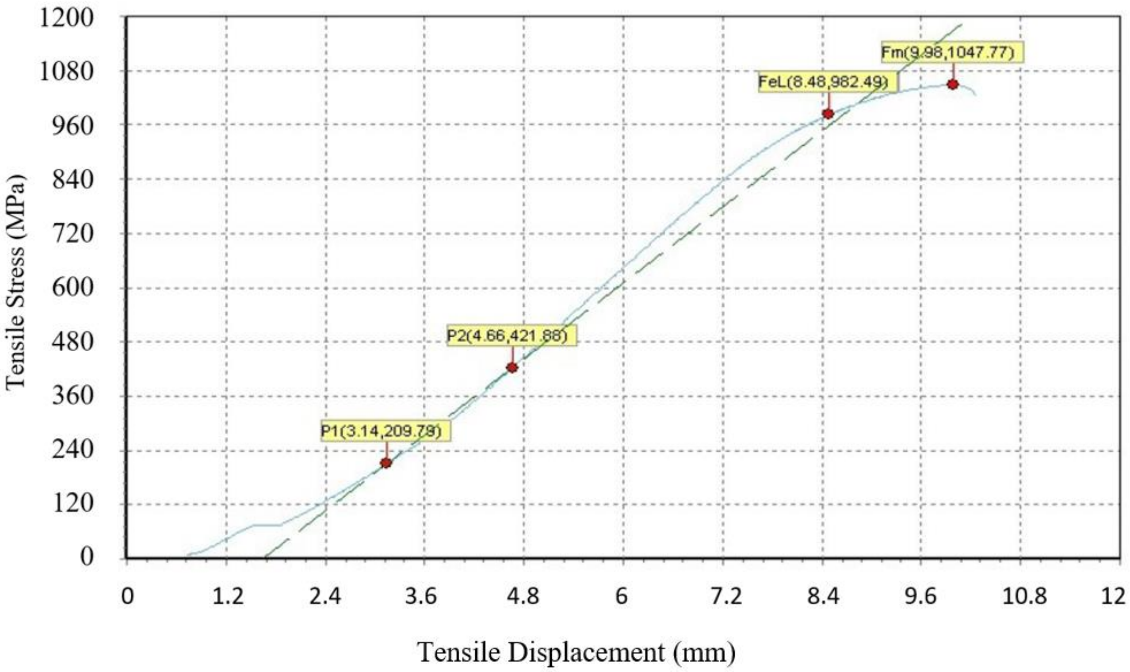

Figure 4.8. Tensile Test Chart of 110-20 Sample

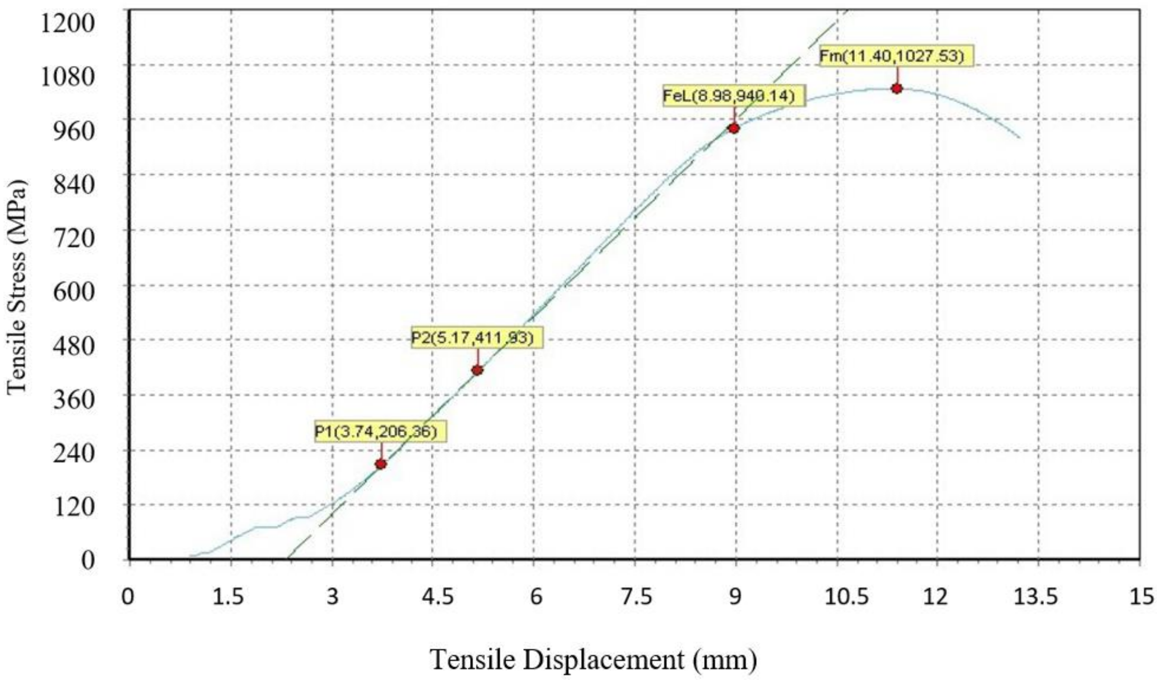

Figure 4.9. Tensile Test Chart of 110-100 Sample

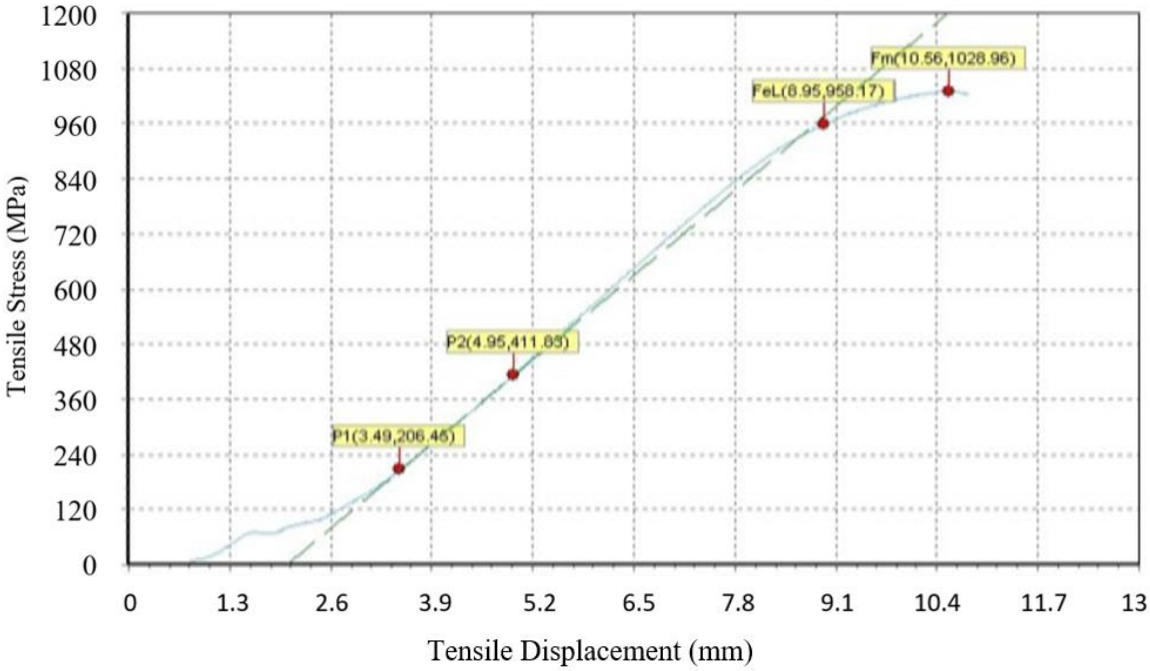

Figure 4.10. Tensile Test Chart of 110-200 Sample

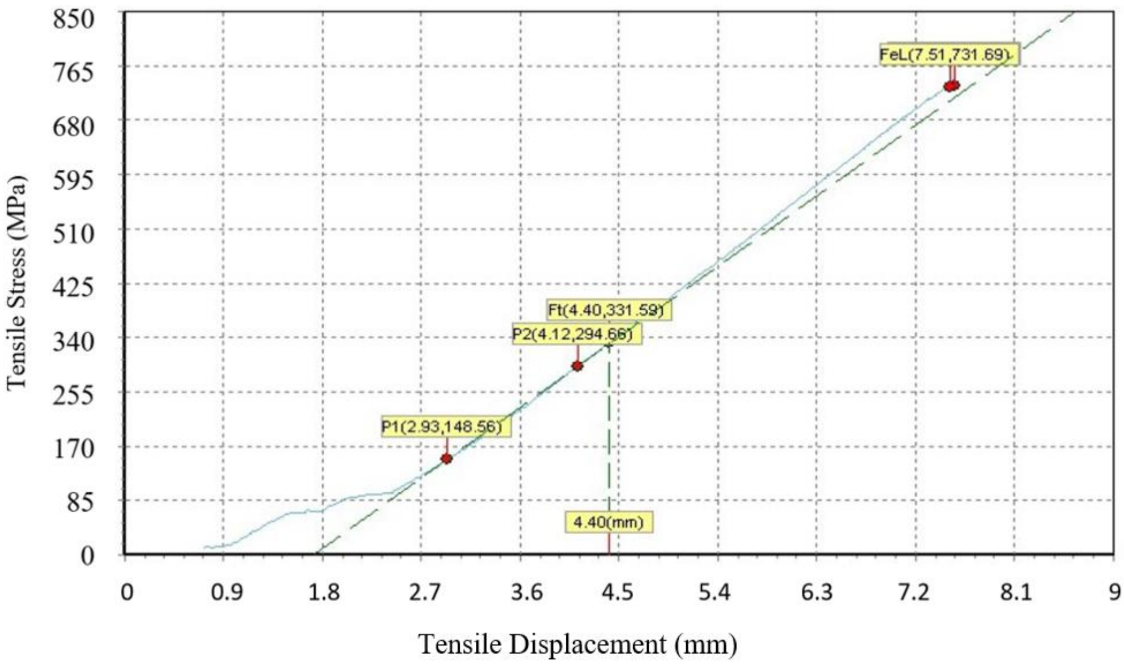

Figure 4.11. Tensile Test Chart of 307-20 Sample

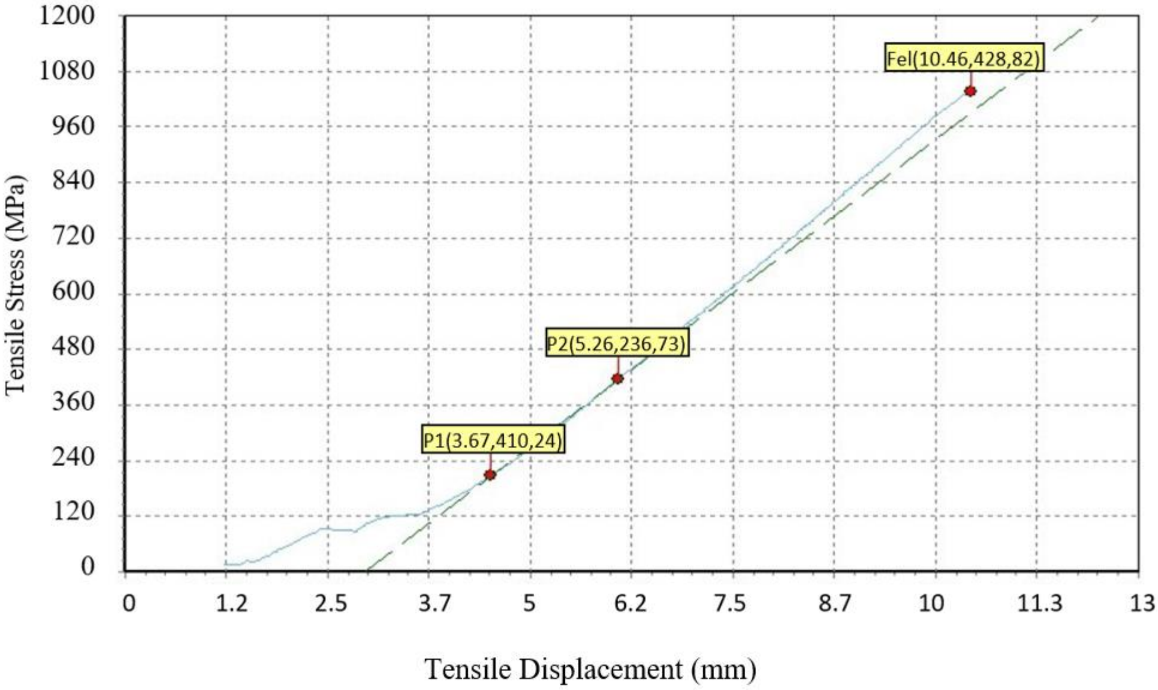

Figure 4.12. Tensile Test Chart of 307-100 Sample

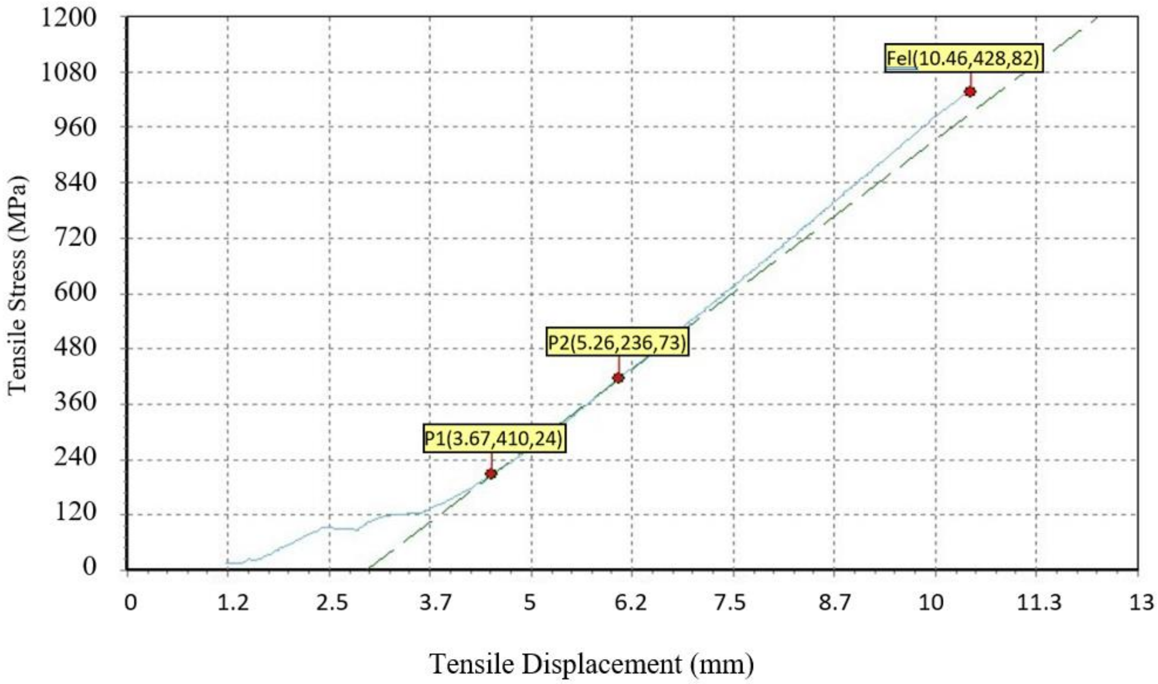

Figure 4.13. Tensile Test Chart of 307-200 Sample

Table 4.7. Tensile Test Results

Sample No	Yield Force (N)	Yield Strength Rp-(N/mm^2)	Tensile Force(N)	Tensile Strength Rm-(N/mm^2)	Location of Fracture
110-20	203765	982	217252,5	1047	Weld Metal
110-100	198785	958	213310	1028	Weld Metal
110-200	195050	940	213102,5	1027	Base Metal
307-20	-	-	152097,5	733	Weld Metal
307-100	-	-	192145	926	Weld Metal
307-200	-	-	204803	987	Weld Metal

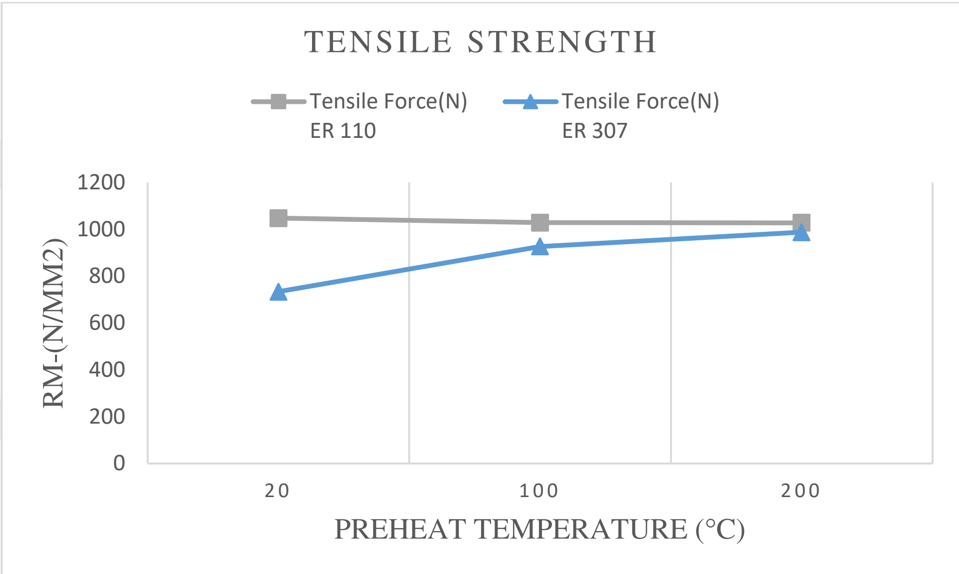

Figure 4.14. Tensile Test Results

4.2. Discussion of Results

Each set of test results unveiled a piece of the larger puzzle surrounding the influence of welding wire type and preheat temperature on the mechanical properties of armor steel. The notch impact tests signified the role of preheating in enhancing toughness, a critical property in armor applications to resist impact loading. The Vickers hardness tests revealed the nuanced relationships between preheating, welding wire type, and hardness, a measure of resistance to permanent deformation. The tensile tests pointed out the interdependencies between preheating, welding wire type, and both strength and ductility, which define the material's behavior under tensile loading. This comprehensive data analysis has deepened the understanding of welding's impact on armor steel and laid the foundation for future research in this field.

4.2.1. Notch Impact Test and the Influence of Preheating and Welding Wire

The notch impact test results reveal a discernible pattern suggesting a contrast between the preheating temperature, welding wire type, and the resultant toughness of the welded joints. The test data, consistent with the existing literature, the preheating within the weld region, consequently influencing the formation of microstructures. Preheating temperatures seem to promote the formation of more brittle, more fragile microstructures, thereby significantly decreasing the toughness of both ER 110 SG and ER 307 welded samples. This finding accentuates the criticality of optimizing preheating temperatures, especially for applications requiring a high degree of toughness to resist impact loading.

4.2.2. Vickers Hardness Test and the Role of Preheating

The Vickers hardness test results unravel a nuanced relationship between preheating temperatures and hardness, which is particularly complex for ER 110 SG welded samples. For ER 110, an initial increase in hardness is observed when preheating temperatures are escalated from 20°C to 100°C. This trend is believed to be due to the formation of a denser and more rigid microstructure within this temperature range.

In comparison, the ER 307 samples display a straightforward, linear increase in hardness with increasing preheat temperature. This could suggest a more stable phase formation in ER 307, with elevated preheating temperatures fostering a progressively harder and denser microstructure.

4.2.3. Tensile Test and the Balance between Strength and Ductility

Tensile testing provides insightful data regarding the interplay of strength and ductility in the context of preheating temperatures and welding wire types In the tests performed on ER 307 welded samples, it was observed that they were broken in the elastic deformation region before reaching the plastic deformation region. Therefore, the yield strength could not be measured. On the other hand, a decrease in yield strength was observed as the preheating temperature increased in ER 110 SG welded samples.

Contrastingly, the behavior of ductility with rising preheating temperatures is starkly different between ER 110 SG and ER 307. ER 110 SG samples exhibit a decrease in ductility, pointing towards a trade-off between strength and ductility. This trade-off could be attributed to the evolution of harder, less ductile phases at higher preheating temperatures. On the other hand, ER 307 samples exhibit an increase in ductility, indicating an advantageous combination of strength and ductility at higher preheat temperatures.

4.2.4. Concluding Remarks and Future Implications

This study, through a rigorous and comprehensive investigation, highlights the critical influence of preheating temperature and welding wire type on the mechanical properties of armor steel. These findings could serve as a valuable resource for future investigations aiming to optimize welding processes for armor steel. Further studies could explore the incorporation of post-welding heat treatments, varying the cooling rates, and employing different welding techniques. Such research would expand the current understanding and potentially lead to refined welding procedures for armor steels, thereby enhancing their performance in demanding applications.

5. CONCLUSION

In conclusion, this study aimed to investigate the influence of preheating temperature and welding wire type on the mechanical properties of high-hardness armor (HHA) steel. Through a comprehensive analysis of the experimental results, several significant findings have emerged, shedding light on the complex relationship between these parameters and the resulting properties of welded joints. The key conclusions drawn from this study are elaborated below:

The impact of preheating temperature on the mechanical properties of welded armor steel has been clearly demonstrated. The notch impact test results revealed a consistent trend of less toughness with increasing preheating temperature. This improvement can be attributed to the reduction of thermal gradients within the weld region, leading to the formation of more ductile microstructures in the heat-affected zone. The importance of optimizing preheating temperature in achieving superior impact resistance in armor steel has been emphasized.

Furthermore, the Vickers hardness test results highlighted the intricate interplay between preheating temperature and hardness. For the ER 110 SG welded samples, an initial increase in hardness was observed as the preheating temperature was raised from 20°C to 100°C. This can be attributed to the refinement of the microstructure and the increased dislocation density within the material (Payares et al, 2008). However, further increase in preheating temperature to 200°C resulted in a slight decrease in hardness, possibly due to the coarsening of the microstructure and the potential formation of softer phases. In contrast, the ER 307 welded samples exhibited a consistent increase in hardness with increasing preheating temperature, indicating a positive correlation between preheating temperature and hardness for this welding wire type.

The choice of welding wire type was found to significantly influence the mechanical properties of the welded joints. The tensile test results showed that the yield strength of the samples welded with ER 110 SG welding wire decreased as the preheating temperature increased. However, the behavior of ductility differed between the two welding wire types. ER 110 SG samples exhibited a decrease in ductility with increasing preheating temperature, likely due to the formation of harder, less ductile microstructures. In contrast, ER 307 samples displayed an increase in ductility, suggesting a favorable combination of strength and ductility at higher preheat temperatures. This highlights the importance of selecting the appropriate welding wire type to achieve the desired balance between strength and ductility in welded armor steel.

In summary, this study has contributed to the understanding of the influence of preheating temperature and welding wire type on the mechanical properties of high-hardness armor steel. The results emphasize the importance of optimizing preheating temperature and selecting the appropriate welding wire type to achieve desired mechanical properties in welded armor structures. The findings can guide future research and development efforts in the field of armor steel welding, aiming to enhance the performance and reliability of welded joints in high-stress applications.

Future research directions could include further investigations into the effects of other welding parameters, such as heat input, welding speed, and post-welding heat treatments, to comprehensively understand their influence on the mechanical properties of armor steels. Additionally, advanced characterization techniques, such as electron microscopy and X-ray diffraction, can be employed to gain a deeper understanding of microstructural changes and their impact on the mechanical properties.

In conclusion, this study has provided valuable insights into the complex relationship between preheating temperature, welding wire type, and the mechanical properties of armor steels. The findings contribute to the existing knowledge base in the field of armor steel welding and provide a foundation for further advancements in this area of research.

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